Hydrogeological constraints on riparian buffers for reduction of diffuse pollution: examples from the Bear Creek watershed in Iowa, USA

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Abstract Riparian Management Systems (RiMS) have been proposed to minimize the impacts of agricultural production and improve water quality in Iowa in the Midwestern USA. As part of RiMS, multi-species riparian buffers have been shown to decrease nutrient, pesticide, and sediment concentrations in runoff from adjacent crop fields. However, their effect on nutrients and pesticides moving in groundwater beneath buffers has been discussed only in limited and idealized hydrogeologic settings. Studies in the Bear Creek watershed of central Iowa show the variability inherent in hydrogeologic systems at the watershed scale, some of which may be favorable or unfavorable to future implementation of buffers. Buffers may be optimized by choosing hydrogeologic systems where a shallow groundwater flow system channels water directly through the riparian buffer at velocities that allow for processes such as denitrification to occur.

Keywords Best Management Practice; groundwater; hydrogeology; nitrate; nonpoint source pollution; Riparian buffers

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Introduction

Riparian Management Systems (RiMS) (Figure 1) have been proposed to minimize the impacts of agricultural production and improve water quality in Iowa (Schultz *et al.*, 1995, 2000). They comprise a toolbox of Best Management Practices (BMPs) that address Nonpoint Source (NPS) pollution. They include multi-species buffers, constructed wetlands, stream bank bioengineering, and, more recently, rotational grazing and boulder weirs (Schultz *et al.*, 2000). The primary goal of these systems is to restore biological and hydrological functions back to previously cultivated or intensively grazed riparian zones. A key element in the RiMS is the multi-species buffer (Figure 2), which typically consists of: 1) a zone of trees nearest the stream to stabilize the bank, sequester chemicals, and improve aquatic habitat; 2) a zone of shrubs to provide woody roots, multiple stems, and biodiversity; and 3) native prairie grasses to intercept runoff from the adjacent cropped field and provide rapidly cycling organic matter for microbial processes (Lee *et al.*, 1999, 2000; Schultz *et al.*, 2000). Palone and Todd (1997) have described buffers as "… one of the most effective tools for coping with NPS pollution."

Studies have generally touted the benefits of buffers in reducing and filtering overland flow for nutrients and pesticides. Their remedial effect on groundwater is less well documented, although it is generally presumed that biological processing occurs as groundwater moves beneath a buffer. Studies elsewhere have shown that the hydrogeology of riparian zones affects their ability to transport contaminants in groundwater (Mengis *et al.*, 1999). Thus, groundwater flow must be understood in order to assess the efficacy of buffers for reduction of NPS pollution (Hill, 1996; Correll, 1997; Schultz *et al.*, 2000). The purpose of

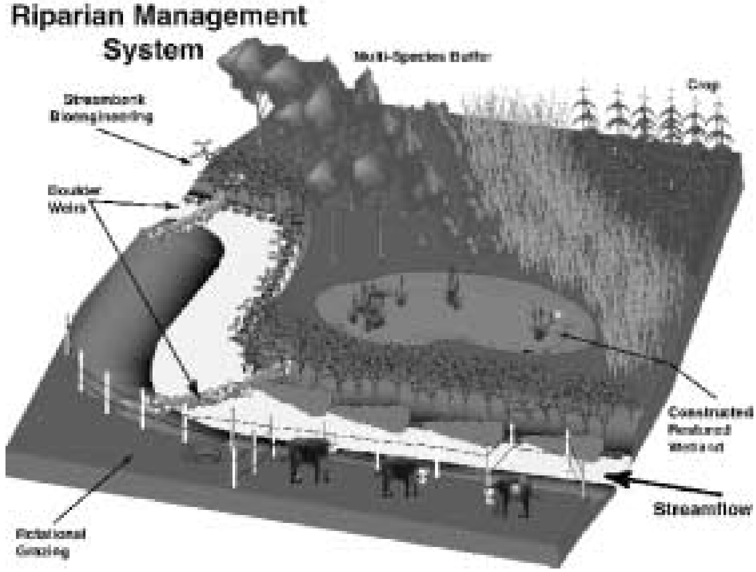

Figure 1 Riparian Management System model consisting of a multi-species buffer that intercepts NPS pollutants; streambank engineering for bank stability; and constructed/restored wetlands that process tile drainage water. Boulder weirs and rotational grazing are recent additions to the RiMS model

this paper is to demonstrate how knowledge of buffer hydrogeology in the Bear Creek watershed of central Iowa is helping us to document buffer effects on NPS pollution in groundwater and optimize new buffer locations.

Bear Creek Watershed

The Agroecology Issue Team of the Leopold Center for Sustainable Agriculture and the Agroforestry Reseach Team at Iowa State University have been implementing the RiMS model in the Bear Creek watershed since 1990 (Figure 3). The watershed contains the most well known buffer demonstration sites in the U.S. In June 1999, the Bear Creek watershed

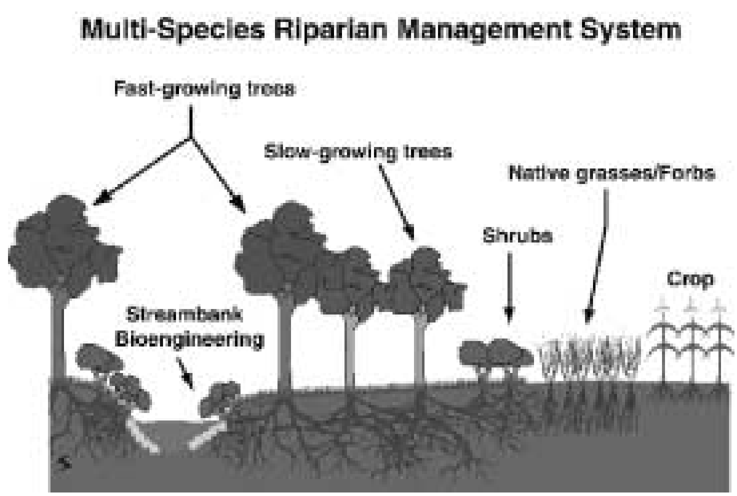

Figure 2 The multi-species riparian buffer model. Zone of fast and slow growing trees and shrubs provide a nutrient sink, wildlife habitat, and bank stability. Native grasses and forbs process surface runoff from upland areas and increase infiltration

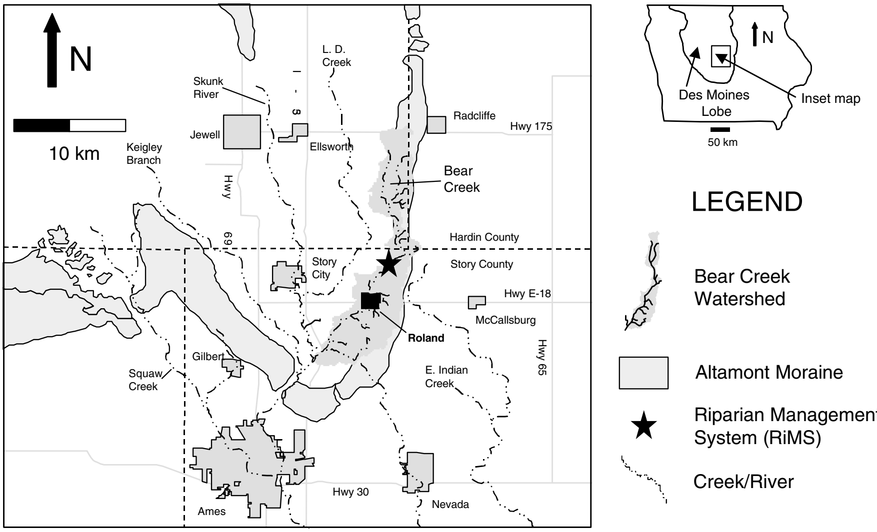

Figure 3 Map showing location of the Riparian Management System and Risdal Farm in the Bear Creek watershed (from Andress, 1999)

was named one of 12 National Restoration Demonstration Watersheds under the EPA's Clean Water Action Plan (www.epa.gov/owow/showcase/bearcreek). Research activity was initiated along a 1,000-m reach of the creek on the private farm of Ron and Sandy Risdal. However, more than 6 km of buffers, most at least 20-m wide, are planted on farms upstream from that site, providing a buffer chronosequence ranging from about one year to 12 years. A photographic record at the Risdal Farm has helped document the impacts of buffer implementation at this scale (Figure 4).

Bear Creek is a third order stream with typical discharges between 0.3 and 1.4 m^3/s. The watershed lies in and adjacent to the Altamont moraine of the Des Moines Lobe, which advanced into Iowa at about 14 ka (Figure 3). The watershed drains 7,661 ha of farmland, most of which is tile-drained and in corn-soybean rotation (about 87 percent). Located within the Des Moines Lobe subregion of the Western Corn Belt Plains ecoregion, the study area was once a tallgrass prairie ecosystem containing wet prairie marshes in topographically low areas and forests along higher order streams.

Methods

The hydrogeology of the multi-species buffer on the Risdal Farm and in Bear Creek watershed has been the subject of a number of studies during the past 11 years. Investigations have included studies of:

- Geology and hydrogeology of the Risdal farm (Ryan, 1993; Simpkins, 1993a, b; Simpkins and Schultz, 1993; Witzke and Bunker, 1993);
- Groundwater interaction with Bear Creek (Simpkins and Caron, 1993; Caron, 1994);
- Hydrogeology and groundwater quality of a cool-season grass buffer (Risdal North) and two multi-species buffers (Risdal South and Strum) (Johnston *et al.*, 1997; Johnston, 1998; Spear *et al.*, 1998);
- Monitoring and modeling of water movement in the unsaturated zone (Twedt *et al.*, 1999);
- Assessing groundwater velocity and denitrification potential beneath a multi-species buffer using natural-gradient tracer tests (Andress, 1999; Andress *et al.*, 1999);
- Application of geophysics and innovative groundwater sampling to optimize placement of future buffers in the watershed (Wineland *et al.*, 2000).

Figure 4 Photographs of the Bear Creek RiMS site at the Risdal farm looking northeast from approximately the same spot prior to buffer establishment in March 1990 (left) and after establishment in June 1994 (right). Land on the right side of the creek had been in cultivation, while land on the left side had been intensively grazed prior to buffer establishment. Rapid growth of riparian vegetation and improvement of bank areas occurred in only 5 growing seasons after buffer implementation

To date, approximately 88 piezometers (wells), 27 minipiezometers, 98 tensiometers, and 17 multilevel piezometers have been installed at the Risdal farm and throughout the watershed for the purpose of characterizing hydrogeology and groundwater quality. A 79.3-m corehole was drilled through the entire Mississippian strata at the farm and piezometers were completed in the borehole. Piezometers consist of Schedule 40 PVC standpipe attached to a factory slotted screen of 0.3 to 3 m in length with slot size openings ranging from 0.3 to 0.6 mm. They are installed with a silica sand (filter) pack to about 0.3 m above the top of the screen; bentonite seals the measurement interval. Groundwater from the monitoring wells has been sampled and analyzed for NO_3-N, NH_4-N, dissolved O_2, temperature, specific conductance, and chloride on a bimonthly to monthly basis, and dissolved organic carbon, pH, and alkalinity on a quarterly basis since summer 1996. The concentration of N_2O, N_2, and CH_4 gases in groundwater was monitored from 1997 to 1999 using the method described in Simpkins and Parkin (1993). Thirty-nine piezometers were installed in 1996 and 1997 as part of a comparative study of buffer hydrogeology. Twelve to 15 piezometers were installed in a cool-season grass buffer on the north side of Bear Creek (Risdal North), a then 7-yr-old multi-species buffer on the south side of Bear Creek (Risdal South), and a then 1-yr-old multi-species buffer 1 km upstream at the Strum farm (Strum site). In 1997, eleven multilevel piezometers and 2 injection wells were installed in the northwest corner of the Risdal North site. The multilevel piezometers consist of a center rod of PVC pipe surrounded by polyethylene tubes each terminating at 0.3-m intervals. Tracer solutions of KBr and KNO_3 were injected in the injection wells and monitored downgradient in the multilevel piezometers (Andress, 1999). Sixty-five electrical resistivity surveys were performed at 37 locations throughout the watershed in 2000 using a Geofyzika ResiStar RS-100m system. Inversion of data with Res2Dinv (v.3.41d) software provided resistivity models for geologic interpretation. Multilevel piezometers were installed with a Giddings probe at various sites to determine the groundwater quality in different hydrogeologic settings and ages of buffers (Wineland *et al.*, 2000).

Results and discussion

Geologic units identified at the Risdal Farm include limestone, sandstone, shale, and chert within the Maynes Creek, Gilmore City, Burlington, Keokuk-Warsaw and St. Louis Formations of Missisippian Age. Shale and chert units are probably effective aquitards for groundwater flow in different parts of the Mississippian aquifer (Witzke and Bunker, 1993). The oldest units identified in the corehole, the Maynes Creek and Gilmore City

Formations, are major aquifers throughout this part of central Iowa. At this location, the potentiometric surface at this depth lies above the land surface, producing flowing artesian conditions. Piezometers in the overlying Burlington and Keokuk-Warsaw intervals also flow at the land surface, but hydraulic heads are less than those of deeper aquifers; hence, a potential exists for groundwater to flow from deeper to shallow bedrock aquifers at the site. This relationship may be the result of the proximity of the site to the South Skunk River, a regional groundwater discharge area. Tritium (^3H) activity and ^{14}C measurements in the deeper aquifers suggest that the water predates atmospheric nuclear testing and may be mid-Holocene in age (Simpkins, 1993b). Thus, these aquifers are part of a more regional flow system that would likely not interact with Bear Creek or the riparian buffers at the farm.

In contrast, the St. Louis Formation is the primary bedrock aquifer for domestic wells in the watershed (Figure 5). It lies from 2 to 7 m below land surface and supports a confined groundwater flow system. Hydraulic conductivity (K) in this unit, particularly in sandstone layers, may approach 10^{-3} ms^{-1}; K in shale units may be 3 to 4 orders of magnitude less. Within this aquifer, groundwater flow appears to be nearly horizontal or slightly upward in the upland areas away from Bear Creek. In contrast, piezometers in this aquifer near Bear Creek may show upward-directed hydraulic gradients, suggesting that groundwater discharges into the creek (Simpkins, 1993b). Caron (1994) showed that upward leakage from the bedrock aquifer to Bear Creek was unlikely because weathered limestone, shale, and unoxidized till underlie the creek bottom and form an effective seal. Flowing artesian conditions occur near the creek because it is the low spot on the landscape and because a shale unit is present in some areas (Figure 5). Tritium data indicate that some groundwater in this aquifer is pre-1953 in age, while some may have been recharged in the 1980s or later. Dissolved O_2 is also present in the aquifer, suggesting more recent recharge (Simpkins, 1993b).

The shallow, unconfined groundwater flow system at the site begins in glacial sediment in the uplands and ends in alluvial sediment (Figure 5). Till (diamicton) at the site averages 53 percent sand, 30 percent silt, and 17 percent clay and represents the Morgan Member of the Dows Formation, which is primarily supraglacial in origin. In contrast, the deeper,

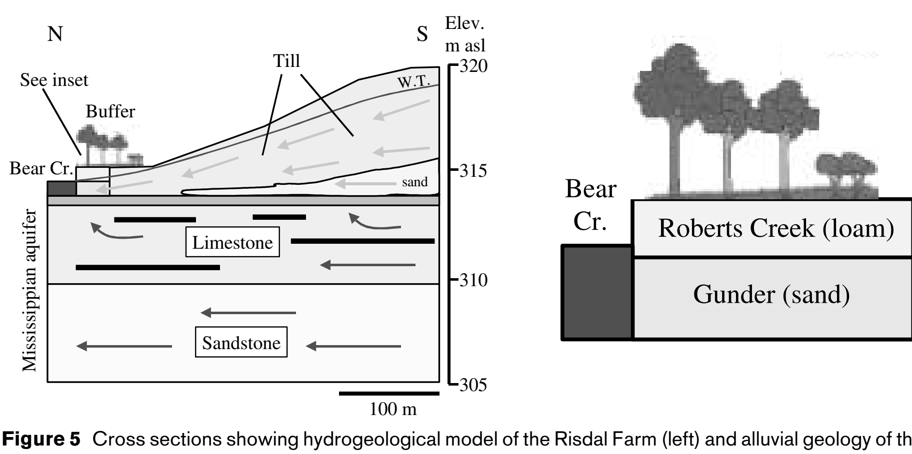

Figure 5 Cross sections showing hydrogeological model of the Risdal Farm (left) and alluvial geology of the multi-species riparian buffer (right). Arrows show general direction of groundwater flow. Groundwater to the shallow system is recharged in uplands. Flow in the till is driven by the hydraulic gradient at the water table (W.T.) through the buffer and to the creek. The creek sits on top of the bedrock surface. Significant discharge of the bedrock aquifer to the creek is suppressed by unoxidized till, shale, and weathered limestone at the top of the aquifer. Most interaction of groundwater with the buffer occurs in the Gunder Member sand (aquifer), where average linear velocities may reach 1 m/d

unweathered (unoxidized) till overlying bedrock shows particle size percentages much closer to those for the Alden Member – the basal till of the Des Moines Lobe. Sand units are often found at the base of the till (Figure 5). Hydraulic gradients at the site taken from nested piezometers suggest downward vertical components of groundwater flow in the upland parts of the site, indicative of groundwater recharge. Because of the confining unit at the base of this aquifer, all groundwater flow and encumbered contaminants from the uplands will discharge into the creek. Groundwater flow is primarily horizontal once it enters the alluvium adjacent to the creek.

Johnston (1998) characterized the hydrogeology of the Risdal North (cool-season grass buffer), Risdal South (then a 7-year-old multi-species buffer) and Strum sites (then a one-year-old multi-species buffer). She identified the alluvium as part of the DeForest Formation of Holocene age. It is composed of the Roberts Creek (loam) and Gunder (sand) Members of the DeForest Formation. The sand unit, which fines upward, is an aquifer with a mean K value of 2×10^{-5} ms^{-1}. Johnston (1998) estimated that residence time of groundwater in the 25-m-wide buffers is between 105 and 281 days.

Andress (1999) corroborated the estimate of residence times using a natural gradient tracer test. He observed denitrification of injected nitrate near the water table within the Roberts Creek and upper part of the Gunder Members. Spear *et al*. (1998) also noted loss of nitrate near the water table. Breakthrough curves indicate that denitrification occurs there because groundwater velocities are lower than near the bottom of the aquifer. The buffer also supplies a source of organic carbon for denitrification (Andress *et al*., 1999). This work suggested to us that sand aquifers might cause groundwater to bypass buffer processes and allow transport of nutrients and pesticides directly to streams.

Conclusions

Anecdotal evidence suggests that multi-species riparian buffers can remediate NPS pollution and improve groundwater quality in agricultural areas. Hydrogeologic investigations at the Bear Creek RiMS site show that buffers have the capacity to remove nitrate from groundwater; however, the amount removed depends on factors such as residence time and a useable organic carbon source. Long residence times promote denitrification, while short residence times promote bypassing. Because multi-species riparian buffers apparently

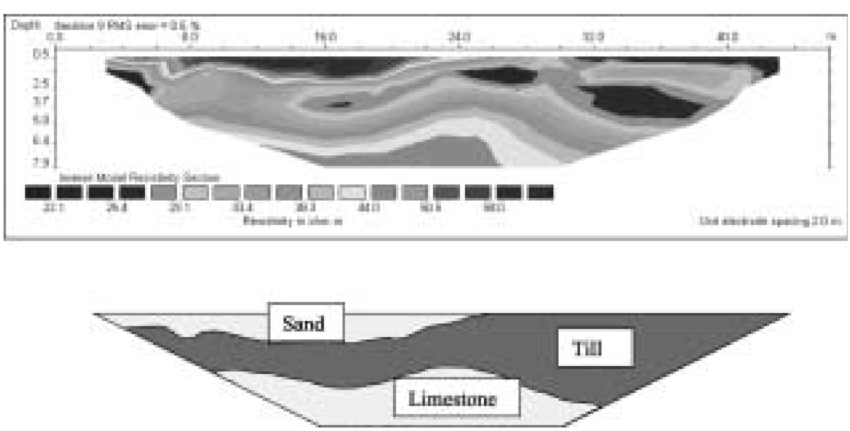

Figure 6 Electrical resistivity section (top) and matching geological interpretation (below). Section is perpendicular to Bear Creek, which is on the left. Vertical and horizontal axes are given on the section and are the same in both diagrams. In this example, the buffer would be installed mostly in sand where residence times might be short. Buffers placed on till may have slower groundwater velocities and provide for greater processing of contaminants. The limestone aquifer, while too deep to interact with the buffer, may provide another source of water to the creek (from Wineland *et al*., 2000)

provide a useable carbon source, *a priori* knowledge of hydrogeology can help optimize the remedial ability of a buffer. We are presently investigating the use of geophysics, specifically electrical resistivity, to ascertain geology in proposed buffer locations prior to installation (Figure 6). This work, coupled with soil coring and multilevel piezometers to monitor water quality at the same site, will help determine the optimal hydrogeologic settings for riparian buffers.

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